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Conservation of and Competition for Water and Nutrients in Semi-arid Agroforestry

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Abstract: Conservation of natural resources and competition between system components in semi-arid agroforestry is reviewed. The possibility to fill under-utilized niches in the landscape with agroforestry is discussed. Examples of processes and mechanisms resulting in conservation or competition on plant level are given. Examples of the resulting outcome of conservation vs. competition are given in seven semi-arid agroforestry systems (savannah, silvopastoral systems, parkland, tree windbreaks, alley farming, contour hedgerows and agroforestry combined with water harvesting). It is concluded that nutrients tend to be conserved in semi-arid agroforestry. Water competition is often reported but there is also scope for water conservation linked to agroforestry. Intensification is needed in the semi-arid tropics because of population pressure, but risk for competition increases as system intensity increases. Ten long-term alley farming – a very resource-use intensive system – experiments were reviewed. It was found that 54% of the 28 "best bet" combinations in these studies resulted in crop yields equal to or higher than sole crop control. These results show that underutilized niches exist and could be developed to increase productivity. Two main options for minimizing competition are: 1) use of more appropriate tree species and 'design' and 2) better tree management. Elements as regards design include broadening the species choice and thereby tree traits (quality of tree litter, resistance to repeated pruning, etc.); to reduce tree-crop interface (increase distance between tree rows and reduce degree of system intensity); practice biomass transfer followed by mulching and, finally; agroforestry combined with water conservation. Tree management options include timely coppicing and root pruning.

Key words: Conservation, competition, semi-arid agroforestry, water, nutrients.

Unsuccessful attempts to improve and promote agroforestry in drylands have led to new re-examinations of the reasons for their failure. Many of these analyses have focused on alley farming or hedgerow intercropping (HI). According to Rao *et al.* (1998), yield increases higher than 15% due to HI are rare in semi-arid tropics because fertility and microclimatic improvements do not offset the large competitive effect of trees with crops for water and nutrients. They argued that progress in the understanding of below-ground interactions should assist in the development of more successful agroforestry systems (recent progress on below-ground

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research is described by Ong *et al*., 1999, this issue). Furthermore, Rao *et al*. (1998) concluded that it would be better to concentrate on tree fallows in order to eliminate direct competition between trees and crops (Rao *et al*.,1999 on soil fertility replenishment in this issue).

Ong and Leakey (1999) attempted to reconcile information on HI with current knowledge of the interactions between savannah trees and understorey vegetation by examining agroforestry systems from the perspectives of resource capture and ecological succession. They concluded that the negative effects of HI on understorey vegetation were due to the high tree transpiration rate and increased interception losses from the fast-growing species and the high tree density used. Thus, trees capture most of the resources at the expense of crops. By contrast, savannah trees are widely scattered and have a high proportion of woody above-ground structure compared to foliage, so that the amount of water 'saved' (largely by reduction in soil evaporation) is greater than water 'lost' through transpiration by trees. Investment in woody structure can improve the water economy beneath the trees, but it inevitably reduces the growth rate of the trees and thus increases the time required for improved understorey productivity. A similar conclusion has been reached on *Faidherbia albida* by Rhoades (1997) in his extensive review of soil improvements by single trees in savannah ecosystems and forests. Ong and Leakey (1999) suggested that the greatest opportunity for simultaneous agroforestry practice is to fill niches within landscape, where resources are currently under-utilized by crops. In this way, agroforestry can advantageously mimic the large-scale patch dynamics and successional progression of natural ecosystems.

In another comparison of dryland agroforestry and savannah ecosystems, van Noordwijk and Ong (1999) argue that agricultural systems should benefit from imitating the structure and function of natural ecosystems, since the latter result from natural selection towards sustainability and are adapted to the erratic rainfall and low fertility. In addition, they suggest that agroecosystems can benefit from mimicking the diversity of natural ecosystems for increased stability. They pointed out that strong competition between plants adapted to the harsh dryland conditions is important for ensuring stability of ecosystem function, unlike the negative view of competition often expressed in agroforestry literature. Therefore, farmers maintain a high diversity of farm options to increase stability rather than optimize farm productivity.

In contrast to the discouraging observations on intensive systems like HI, there is consistent evidence to show improved soil water and nutrient status under single mature tree canopies in savannah areas of Africa, Central and South America and North America (Belsky and Amundson, 1997; Rhoades, 1997). There is strong evidence that nutrient redistribution by the deep or extensive root systems, as well as capture of resources by tree canopies, are responsible for soil nutrition beneath savannah species like *Prosopis juliflora* (Tiedemann and Klemmedson, 1973). In Kenyan savannahs, Belsky (1994) observed improved micro-climate, greater soil biotic activity and

N mineralization, greater infiltration rate and greater beneficial effects on understorey vegetation in more xeric environments (from 750 to 450 mm).

One practical aim of agroforestry research is to develop better agroforestry systems, which maximize conservation and utilization of growth resources and minimize the negative effects of competition. This is particularly important when one component of the system (food crop vs. tree) is more valuable to the land user than the other. In this paper, we explore whether changes in the tree management, tree species and the quality of tree litter used for mulching can influence the conservation of and competition for water and nutrients sufficiently to mimic the positive effects observed in natural savannahs. Other growth factors, besides nutrients and water, are also relevant for semi-arid agroforestry but are only briefly touched upon here. 'Conservation' in this context refers to both the savings in water and nutrient resources, which would otherwise be lost or are unavailable to the understorey species. Competition here refers to the reduction in growth or yield of one component species as a result of interference by greater capture of resources, in particular water and nutrients or light, by the more aggressive species, usually the tree.

The paper focuses on semi-arid areas. Much of the earlier work in agroforestry has concentrated on sub-humid to humid areas. However, it is important not to generalize results from one climatic zone to another. Two general differences between the semi-arid tropics and humid areas influencing agroforestry should be given special consideration: (1) competition between tree and crop, especially for water, is likely to be greater in the semi-arid tropics than in more humid areas (van den Beldt, 1989), and (2) soil constraints often differ between the semi-arid tropics and more humid areas (Szott *et al.*, 1991). However, where information is lacking in semi-arid areas, we illustrate with examples from other climatic zones.

The Plant Level

Conservation of growth resources and soil improvements by trees

In his recent book on 'Agroforestry for Soil Management', Young (1997) summarized the beneficial effects of trees on growth resources and on soil properties under these four major headings:

- Increased inputs to the soil
- Reduced losses from the soil
- Improved soil physical and chemical conditions
- Promoted soil biological processes.

In his extensive literature review on these topics, stated as various hypotheses in his earlier book (Young, 1989a) and further expanded by Sanchez (1995), Young concluded that most of these have been substantiated by recent agroforestry research. In this review, we focus on recent advances in the semi-arid tropics, using primarily examples from sub-Saharan Africa, being the most intractable ecoregion for agroforestry innovations and development.

The ability of trees to maintain or even increase levels of soil organic matter and to contribute to the soil nitrogen pool through nitrogen fixation has been unequivocally proven. Atmospheric deposition accounts for a substantial input of nutrients in humid areas, but potential contributions from dust storms in arid and semi-arid areas, which could be significant, are little documented. There are numerous accounts of the substantial input of organic matter (leaves, roots, twigs) provided by mature trees and forests and the enrichment of the soil directly beneath the tree canopies. In his review of both forest and savannah literature, Rhoades (1997) described the dominant factors and pathways that trees can influence soil formation and the decomposition of organic matter. He concluded that "the challenge for agroforesters is to determine under what conditions positive tree effects will accumulate simultaneously within active farming systems and which require rotation of cropping and forest fallows".

The replacement of forests by agriculture usually results in large losses of soil and nutrients because reduced plant cover leads to erosion, higher leaching, increased runoff and substantial soil evaporation. It has long been recognized that many trees have deeper and more extensive root systems than the roots of common agricultural crops, inferring a potential of trees to recycle nutrients from depth, which would otherwise be lost. Naturally, recent research has focused on the deep-rooting attributes of trees (Schroth, 1995; van Noordwijk and Purnomosidhi 1995; Odhiambo *et al.*, 1999). Indirect evidence from natural systems including trees suggests that leaching losses for soluble nutrients such as nitrate are low in drylands (often as low as 5 to 10% of the nutrients recycled). Therefore, lateral root extension is considered to be more important than deep rooting (Breman and Kessler, 1995). On the other hand, only around 40% of the nutrients applied as fertilizers to crop monocultures are typically taken up, so the potential for improvement is substantial (Young, 1989b). It should be noted, however, that the remaining nitrogen not taken up by the crop is susceptible to leaching, especially in sandy soils and during high rainfall events. Some researchers have suggested that there is little potential to take up and recycle P from below the rooting depth of crops because plant extractable P is normally low in subsoil (Buresh and Tian, 1997).

Nutrient leaching could be reduced by the extensive root network, called the 'safety net concept', of agroforestry trees and the protection offered by surface tree litter. This has been shown in studies of alley farming and improved fallows in sub-humid to humid areas and in coffee or cacao grown under shade trees, especially in Central and South America (Beer *et al.*, 1997). We are not aware of any comparable study on leaching losses from the semi-arid tropics. Deans *et al.* (1995) indicate that a safety net could work in certain semi-arid conditions, e.g., in Senegal leached nitrate was found to accumulate in deep soil layers. Neem fine roots were present as deep as at 30 m and could potentially recover this.

Reduction in water loss in semi-arid agroforestry is of utmost importance. In semi-arid regions, crops often use only a small fraction of the seasonal rainfall since there can be substantial losses of water via soil evaporation, runoff and drainage (Wallace, 1996). In the semi-arid Africa and India direct soil evaporation accounts for 30 to 60% of rainfall. For example, Breman and Uithol (1984) noted a loss of up to

50% of rainfall in soil evaporation and up to 25% of rainfall in surface runoff in dry Sahelian rangelands. If some of this rainfall could be 'saved' or retained in the soil and used as transpiration, yield could be increased. In agroforestry the major option is to reduce soil evaporation by shading from tree canopies or by mulching with tree litter. Measurements at ICRAF's Research Station in Machakos (annual rainfall of 760 mm) showed that a tree canopy (leaf area index, LAI of 2.5) could reduce soil evaporation by 35% as compared to bare soil, equivalent to 21% of annual rainfall (Wallace *et al.*, 1999). At lower LAI of 1, which is more typical of the sparse vegetation in drylands, the saving due to tree shade is only 6%. Although this fraction of the rainfall appears low it is close to the total rainfall utilized by a pearl millet crop in a watershed in Niger, where deep drainage and soil evaporation accounted for about 40% each of the seasonal rainfall (Rockstrom, 1997). The savings in soil evaporation by tree shading across three contrasting sites was modeled, which showed that the greatest saving in percentage was when rainfall was very low (less than 500 mm), and least when rainfall exceeded 1000 mm (Fig. 1).

An example from a very dry climate, however, did not show higher soil moisture levels under savannah trees as compared to open areas (Alstad, 1991). Other processes and effects by which trees may increase water availability include mulching, so that trees improve soil structure and thereby infiltration, enhance uptake by deep roots and reduce soil moisture variability (Breman and Kessler, 1995).

Compared to the considerable studies on soil fertility research, little attention has been paid to the impact of semi-arid agroforestry on soil biology and in particular soil meso- and macrofauna. Mulch, often used in agroforestry, has been reported to attract termites. This would be advantageous if termites prefer mulch over the crop. On the other hand, if crop is weakened by stress termites attracted to mulch might cause plant damage (Douglas, 1991). The role of earthworm in the restoration and maintenance of soil properties and their impact on soil genesis and topsoil formation is well documented. Hauser *et al.* (1998) reported five time more casting under leucaena hedgerows compared to no-tree controls in south-western Nigeria (rainfall 1200 mm). However, casting activities were not significantly affected by different tree species after 5 years and the authors suggested that shading effects and low soil disturbance are more beneficial for earthworm activity than food supply as tree organic matter.

Mulching with leaves and prunings from the trees is an important part of many agroforestry practices and has the potential to influence all beneficial effects by trees mentioned by Young (1997). Mulching in the semi-arid tropics has generally been shown to:

- conserve soil moisture (Adetunji, 1990; Bristow and Abrecht, 1989; Carter *et al.* 1992; Gajri *et al.*, 1994; Zaman and Mallick, 1991),
- decrease soil temperature (Adetunji, 1990; Bristow and Abrecht, 1989; Gajri *et al.*, 1994),
- decrease runoff and soil erosion (Smith *et al.*, 1992; Sur *et al.*, 1992; Vogel, 1993),

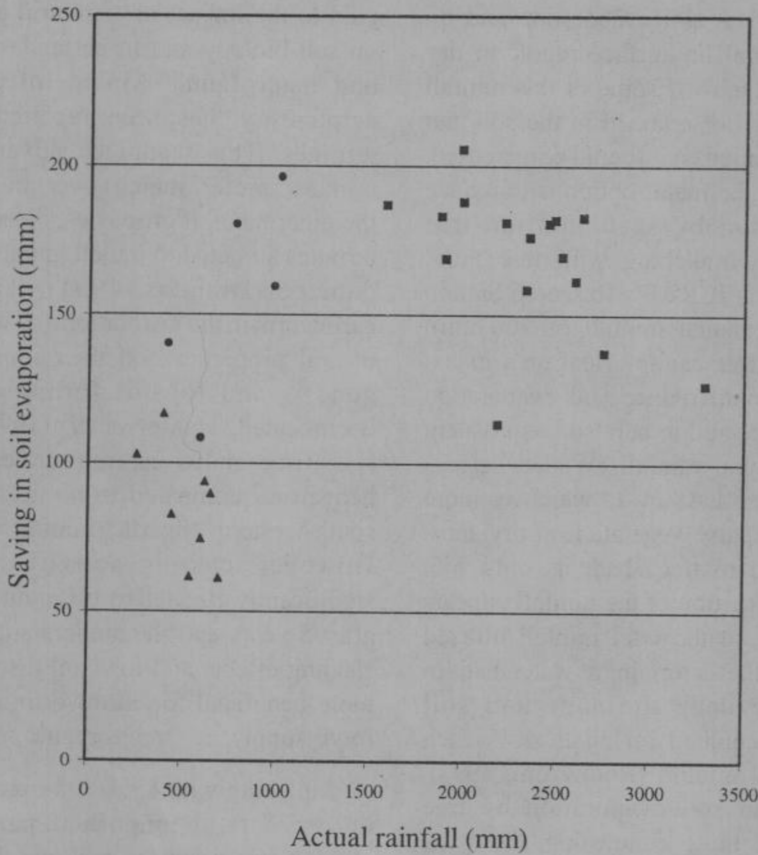

Fig. 1. Saving in soil evaporation by tree shade calculated from three different sites in Sadore, Niger (triangles) and two sites in Kenya (Kimakia, squares; Machakos, solid circles). From Wallace et al. (1999).

- trap nutrient-rich, wind-borne dust (Drees *et al.*, 1993; Geiger *et al.*, 1992),
- enhance the abundances of the soil macrofauna, leading to increased decomposition rates and tunneling that increases infiltration (Hoare, 1992; Reddy *et al.*, 1994; Robertson *et al.*, 1994),
- help recycle nutrients following termite and microbial decomposition (Geiger *et al.*, 1992) and
- improve root growth (Gajri *et al.*, 1994).

Most studies on mulching in the semi-arid tropics have concentrated on nutrient-poor, dry mulch like straw. It is interesting to use these studies as reference since semi-arid studies on nutrient-rich leaf mulch are still rather rare. As regards the crop yield response to straw mulch, results are variable. Mulching-induced improvements in yield have often been ascribed to increased soil moisture (Adetunji, 1990;

Table 1. Schematic presentation of the mulch effects of six different treatments and the resulting grain yield response (arbitrary scale). Mulches were applied at 5 t dry matter ha^{-1} during 1992 – 1994 at Saria station, Burkina Faso (after Tilander and Bonzi, 1997)

	Neem	Neem + compost	Compost	Acacia	Wild grass	Control
Increased soil water	+++	+++	0	+++	+++	0
Lowered soil temperature	+++	+++	0	+++	+++	0
Increased soil nutrients	+++	+++	+	+	+	0
Increased yield	+++	+	+	+	0	0

Gajri *et al.*, 1994; Patra *et al.*, 1993; Zaman and Mallick, 1991). In addition, yield increases have been attributed to the ability of mulch to enhance nutrient availability (Bationo *et al.*, 1993; Patra *et al.*, 1993; Rebafka *et al.*, 1993), increase root growth (Gajri *et al.*, 1994) and decrease soil temperature (Adetunji, 1990).

Although mulching increased soil moisture, reduced runoff and soil erosion compared to unmulched plots, crop yields were sometimes negative or neutral (Smith *et al.*, 1992; Vogel, 1993). One of the most common reasons cited for the lack of crop response is the low recovery of the nitrogen from the tree prunings: usually between 10 to 30% of the amount applied (Palm, 1995). It has been suggested that the low recovery of N is due to the lack of synchrony between N demand by the crop and N release from the prunings, but recent studies in semi-arid (annual rainfall of 750 mm) Zimbabwe indicated that incorporation of prunings at planting is sufficient to ensure optimum N recovery, increasing N recovery from 16 to 27% with 5 t ha^{-1} of leucaena (Mafongoya *et al.*, 1997b). They reported yield increases from 1.67 (untreated control) to 5.49 t ha^{-1} (with prunings of leucaena).

In a study on the central plateau of Burkina Faso, sorghum yields in a non-fertilized field showed up to a four-fold increase during three consecutive years (mean of five treatments) when mulched with leaves from *Azadirachta indica, A. Juss* (neem) or *Albizia lebbeck* (L.) Benth. (albizia) with leaf applications corresponding to 75 kg N ha^{-1} (Tilander, 1993). This N dosage was roughly equivalent to 3.7 t dry matter ha^{-1} for neem and 2.7 t dry matter ha^{-1} for albizia. Leaf amounts corresponding to 25 kg N ha^{-1} or 50 kg N ha^{-1} also influenced yields significantly, resulting in higher yields in five of the six cases.

Another study (Tilander and Bonzi, 1997) examined a combination of mineral fertilizers and organic fertilizers, including agroforestry leaf mulches. It was shown that both nutrient-rich (neem leaves and neem leaves + compost) and nutrient-poorer mulches (wild grass and *Acacia holocericea* Cunn.ex G. Don phyllods) significantly conserved water and reduced temperatures. Plots treated with neem leaves, neem leaves + compost or compost alone (bringing approximately equal amounts of N and K, while P differences were negated by the application of mineral fertilizers) gave higher sorghum yields than three nutrient-poor treatments (Table 1). Thus, yields did not always increase in spite of increased soil moisture and decreased temperatures. It was concluded that nutrients were more limiting than soil water or temperature. The highest yields were achieved with treatments that combine high nutrient delivery with water conservation and temperature reduction, namely mulch from neem leaves.

The two studies in Burkina Faso permit a comparison between mulch effects on a non-fertilized field with those on a field receiving a combination of mulch nutrients and basal rates of mineral fertilizers. One of the studies focused on nitrogen content and the other on dry matter. However, since the materials in both studies were analyzed for both dry matter and nitrogen, conversion factors can be used. It was found that the mulch effects on yield, calculated on both dry matter and on nitrogen bases, were much higher compared to the control in the experiment with no mineral fertilizers than in the one combining organic and mineral fertilizers. This agrees with the conclusion that nutrients are more limiting than water under these experimental conditions, since nutrients from the mineral fertilizers were likely to mask the effects caused by the mulch.

In drylands, integration of soil and water management is of central importance. As mentioned, studies in the Sahel suggest that part of the large evaporative losses of water can be attributed to insufficient soil nutrient content (van Keulen and Breman, 1990). One way to cope with the present reality for many farmers (no external inputs) and take advantage of positive interactions by mulch in water and nutrient conservation would be to concentrate nutrients within the system, i.e. biomass transfer (Tilander, 1993; Young, 1997). This could be considered as the creation of a new niche, in line with the argument proposed by Ong and Leakey (1999).

Combinations of organic fertilizers, like mulch from agroforestry, with inorganic fertilizers have often been suggested (Sanchez, 1994; Palm *et al.*, 1997), the paramount reason being the amount of available biomass is limited. Well-managed agroforestry can provide greater inputs of organic matter to semi-arid farming systems. However, even with intensification of dryland agroforestry available organic fertilizers are not likely to contain enough nutrients, especially P (Buresh *et al.*, 1997), to cope with both crop needs and soil deficiencies.

The literature on the combination of organic nutrients with external input of inorganic fertilizers has been described by Palm *et al.* (1997), who concluded that despite beneficial effects of such combinations disadvantages still exist. Available studies rarely permit a systematic analysis of the interaction between properties and we are still far from understanding what determines optimal combinations of organic and inorganic fertilizers. A further complication in dryland farming systems – not treated in-depth in the above review – is the capacity of agroforestry organic nutrients applied as mulch to conserve water by reduced evaporation and runoff. As mentioned earlier (Tilander and Bonzi, 1997), mulching materials that provide both high nutrient content and conserve soil water should result in higher crop yield. The water-conserving aspect of the organic fertilizers should be integrated in the research framework proposed by Palm *et al.* (1997).

Competition between trees and crops in drylands

Nutrients: Direct competition between trees and crops for nutrients was rarely demonstrated in dry or humid climates (Young, 1997). There may be other explanations than non-existence why nutrient competition has not been registered. The major reason is the formidable cost of nutrient and isotope analysis. Root measurement is an indirect way of demonstrating competition, but such studies are very tedious and time-consuming and therefore rare (van Noordwijk *et al.*, 1996). The isotope method is a more direct way to demonstrate the fate of added nutrients. Studies of natural abundance of ^{15}N does not consistently demonstrate a direct transfer of tree-fixed N to the crop (Jonsson *et al.*, 1999), indicating either competition with trees or that the majority of the nutrients remain in the soil and is not immediately available to the crop. Haggar *et al.* (1993) reported as high as 80% of ^{15}N remained in the soil in humid Costa Rica. Recent results with ^{32}P in 8-year-old trees of jackfruit indicated that a lack of competition may suggest that tree root density might not be sufficient to absorb the nutrients in the soil (Jamaludheen *et al.*, 1996).

Buresh *et al.* (1997) conclude that P stocks have been successively depleted in sub-Saharan Africa and that P is now a limiting nutrient in many soils of the semi-arid tropics. This fact naturally increases the risk for competition for P. Phosphorus cycling through organic-based systems like agroforestry is insufficient, however tight-cycled they may be (Palm, 1995; see review on sub-Saharan Africa by Buresh and Tian, 1997; Mafongoya *et al.*, 1997a). The addition of mineral P in fertilizers has been suggested by many workers (Buresh *et al.*, 1997; Sanchez, 1994). There are beneficial effects by combining P application with the organic material obtained through agroforestry (Palm *et al.*, 1997) but further studies should determine optimal combinations.

Generally, soil-fertility depletion is serious for many nutrients in sub-Saharan Africa (Odhiambo *et al.*, 1999). Obviously the risk for nutrient competition increases in a situation of scarcity. In conclusion, much circumstantial evidence indicates that it would be prudent to consider the possibility of nutrient competition in semi-arid agroforestry. It has to be considered as one of the factors in competition studies in semi-arid areas.

Water: The water balance of agroforestry systems is more complex than of any other agricultural system studied so far, and very little is known about the way in which available water is partitioned between the tree and crop component in agroforestry systems (Wallace, 1996). Wallace *et al.* (1999) observed a reduction in 8 to 10% of total rainfall by canopy interception, which could be described as a competitive effect by trees, since this was unavailable for transpiration. However, this has to be subtracted from the larger savings in soil evaporation due to the shading by the tree canopy (Fig. 1).

Many scientists agree that competition for water between trees and crops is a major problem in areas with rainfall below 800 mm y^{-1} (Ong, 1995; Rao *et al.*, 1998; Young, 1997). Therefore, considerable research efforts have been invested to understand the above- and below-ground processes involved in order to develop better management practices for intensive agroforestry systems, particularly hedgerow intercropping (Lehmann *et al.*, 1998; Ong *et al.*, 1996b).

Ong and his co-workers conducted a series of investigations at Hyderabad, India, and later at Machakos, Kenya, on the partitioning of water use by trees and crops using sap flow technologies. Recent development in methods now permits this (Ong *et al.*, 1996a). The technology is appropriate for use on trees and has been successful on crops with sturdy stalks like sorghum. After careful calibration, it has been reported that it is possible to use also on smaller crops like rice and cotton. They concluded that agroforestry systems can greatly increase the utilization of rainfall compared to annual cropping systems, largely by extending the growing season. However, competition for below-ground resources between trees and crops greatly reduced crop yields and such findings led to a series of root investigations in search of spatial complementarity, to be discussed by Odhiambo *et al.* (1999).

The System Level

Competition and conservation in major agroforestry systems in drylands

In the following sections, conservation and competition in the major existing agroforestry systems in the drylands are briefly presented, with a few selected examples given. A full description of each agroforestry system is made by Rocheleau *et al.* (1988).

Savannah

The common vegetation type in the semi-arid tropics is the savannah, which is dominated by grasses with a few scattered trees. Primary productivity on the savannah (mainly of the grass component) is closely correlated with precipitation. Thorough knowledge of natural systems can contribute to understanding the more intensively managed agroforestry systems (Ong and Leakey, 1999; van Noordwijk and Ong, 1999). For example, in a savannah, trees often interact in a neutral or positive way (commensalism or mutualism) with non-woody vegetation. Early studies of the natural *Acacia karoo* savannah in southern Africa suggest that trees and grasses do not seem to compete for water in the upper 20 cm soil horizon (Stuart-Hill *et al.*, 1986) and this association has been used as an example of niche separation. However, recent studies of root distribution and water extraction patterns suggest otherwise, implying that this is an example of competitive association maintained by frequent fires (Scholes and Walker, 1994).

Silvopastoral systems

Silvopastoral systems are most common in the drier parts of the semi-arid tropics. Trees and bushes contribute browse and fodder, highly valued during the dry season. These regions are often subjected to severe soil degradation, owing to drought and overstocking. Tree planting schemes here have encountered problems of both biological and social nature (Kerkhof, 1990). Large areas are browsed extensively by livestock, therefore, tree plantings are often destroyed by grazing animals.

In Chile, a successful planting scheme demonstrated the potential of agroforestry to increase input to the system by increased resource capture in photosynthesis and thereby, in fact, exploitation of an under-utilized niche. 37,000 ha was planted with *Atriplex nummularia* and *A. repanda* in zones with rainfall of 50 to 400 mm (Ormazabál, 1991). In high-altitude areas, *Polylepis besseri* and *Polylepis tarapacana* were planted, and in the extremely dry zones, *Prosopis chilensis* and *Prosopis tamarugo* were used. It was estimated that the introduction of *A. nummularia* plantations increased the carrying capacity from 0.5-1.2 to 3 sheep or goats per hectare.

Parkland systems

Many studies on soil nutrient status in cultivated parkland savannahs have shown that soils under trees are richer in nutrients compared with soils from open fields (Alstad, 1991; Boffa, 1995; Jonsson *et al.*, 1999; Kater *et al.*, 1992). The *Faidherbia albida* system is a well-known example of a cultivated, low-intensive agroforestry system in which microclimate, as well as physical and chemical properties of the soil under the trees, have benefited crop growth. Higher crop yields have also been recorded, with increases of 100% for sorghum (Depommier *et al.*, 1992 in Burkina Faso; Rhoades 1997, in Malawi), 100 to 150% for pearl millet, and 45% for groundnut (CTFT, 1988).

Windbreaks formed by trees

Windbreaks in dry areas have often been reported to enhance yields of the crops grown between the widely separated tree lines (Benzarti, 1989; Jebari, 1989). In the Majja Valley Project in Niger, pearl millet grain yield increased by 20% between 5-year-old windbreaks of *Azadirachta indica* spaced 100 m apart. However, after five more years, crop yields were no longer significantly higher, possibly because competition had increased between the fifth and tenth year of the study (van den Beldt, 1989). A recent comparison of neem windbreaks in Majja valley and at Sadore, Niger, suggests that access to the shallow water-table at Majja valley (6 to 8 m) is highly important for the beneficial effects on crop yield. However, at Sadore, the water-table is too deep (35 m) for tree roots resulting in extremely harmful effects on crops (Smith *et al.*, 1998). Therefore, agencies planning to establish windbreaks in drylands should consider carefully the source of water used by windbreak trees, tree root architecture and the accessibility of groundwater and deep reserves of soil water. Choice of species is also important. Smith *et al.* (1998) used sap flow gauges to monitor water uptake by trees, commonly used for windbreaks in the Sahel and found that neem used only about half the water (per unit leaf area) used by *Acacia holosericea*, a tree which was previously perceived to be highly drought tolerant.

Alley farming

When interest in agroforestry as a research theme developed in the 1970s, most trials were set up in humid to sub-humid zones. Kang *et al.* (1985) at IITA, Nigeria, showed that in alley farming systems acceptable levels of both production and soil fertility could be maintained. In consequence, great emphasis was placed on these systems, with a heavy reliance on the nitrogen-fixing tree, *Leucaena leucocephala* (Lam.) de Wit. In some cases, attempts were made to transfer techniques to the drier regions without giving sufficient consideration of the specific demands in these ecosystems. It is now apparent (Ong, 1991; Ong *et al.*, 1991; van den Beldt, 1989) that special attention needs to be focused on the interactions between trees and crops under the semi-arid conditions, and that agroforestry practices developed in sub-humid conditions must be modified before applying them in semi-arid areas.

In systems with high tree density, such as the alley farming system, competition between trees and crops is the most intractable problem. A few examples from the vast literature are given below. In a review of alley farming in semi-arid India, with rainfall mean in the range of 560 to 878 mm (Singh *et al.*, 1989b), it was concluded that alley cropping consistently suppressed crop yields. With closely spaced alley (3.8 m), crop losses reached up to 70%, therefore, wider alleys (more than 7.8 m) were recommended. They concluded that farming with wide alleys holds promise in the semi-arid tropics, in view of the stable income gained through the sales of tree products and the total economic returns of the agroforestry system, calculated to be twice that of sole cropping. In contrast, another study from India (Rao *et al.*, 1991) found that the planting of *Leucaena leucocephala* trees in alleys offered little or no economic advantage over the planting of the trees and agricultural crops in separate blocks due to competition for water between trees and crops. Rao *et al.* (1998) reviewed long-term (four years or more) semi-arid alley farming and found yield increases compared to the control in the best treatments in four out of eleven cases.

In an attempt to get at fuller picture, we re-examined in more detail the available semi-arid alley farming studies mentioned by Rao *et al.* (1998), by Young (1997) as well as some new material (Table 2). Only studies, covering four or more years, were examined. Papers published in refereed journals have been preferred. 'Best-bet' treatments were chosen and normally crop mean yields for those over the 4+ years of the study are presented. However, in many Indian studies where crop rotation is practised, we have listed results even if crop yields origin from only one or two years. When several tree species appear in a trial, we have mentioned them all in order not to lose valuable information. Best bet is then the treatment of a certain species (spacing, fertilization practice), which was the best.

Half (54%) of the best bet studies are equal to or better than the control, but in studies from India and Kenya yields are especially low. In 29% of the best bet studies the yields were equal to or better than the control. Common factors for the studies from India and Kenya are tree species (only *Leucaena leucocephala*) and bimodal climate (where each crop in reality receives less rain than inferred by the figures of annual rainfall). A wide diversity of crops has been tested and does not seem to influence on the outcome of the results.

Results are more encouraging from the other four countries where studies are available (Burkina Faso, Malawi, Rwanda and Tanzania); 79% of the best bet studies yielded equal to or better than the control. A diversity of tree species has been tested (9) but crop diversity is less.

The analysis shows that there is scope for outweighing competitive effects by complementary effects in high density agroforestry systems like alley farming. This means that there is room for introducing and/or utilizing new niches in this climate, which conserves growth resources to such an extent that any competition present is negated. The aim of this paper is not to analyze in-depth why alley farming works or not. However, in general, appropriate height and timing of the pruning is central, early pruning being advantageous. Differences between the control and treatment are generally higher in non-fertilized experiments, which is of interest to farmers unable to finance external inputs. The importance of testing a greater diversity of tree species is clear. A few examples are given to illustrate the above points.

In India, Singh *et al.* (1989a) showed that negative effects on sorghum, cowpea and castor in alleys of *Leucaena leucocephala* were completely eliminated by introducing a polythene root barrier of 0.3 m from the tree row at a depth of 50 cm. Root pruning through ploughing has been shown to have similar beneficial effects (Korwar and Radder, 1994). Hocking and Rao (1990) showed that pollarding *L. leucocephala* trees could reduce the negative effects on sorghum and be more economical.

In a six-year study from Burkina Faso, timing of the tree coppicing was shown to be a central factor for reducing competition (Tilander *et al.*, 1995). Coppicing alley farmed trees at 30 cm approximately one month after planting of the sorghum crop resulted in significantly higher crop yields than coppicing after three months (Tilander *et al.*, 1995). Other management options for improvement include species choice, distance between tree rows and degree of system intensity (alley farming compared to trees in farmed parkland). The study showed that competition was completely eliminated in alleys at 8-m spacing of *Azadirachta indica.* Crop yields in alleys of *A. indica* and *Albizia lebbeck* were generally considered acceptable (often higher than 80% of control yields). *L. leucocephala* alleys, however, yielded poorly. Further, narrow alleys (5 m) yielded higher for the nitrogen-fixing *A. lebbeck* (indicating a N-effect that overtook competition in narrow alleys), while wider alleys yielded higher for *A. indica* that does not fix nitrogen (indicating that competition reduction was necessary to take advantage of conservation effects in this case). *A. indica* trees in a spacious parkland system were also studied and here it was shown that competition close to early coppiced trees were not only eliminated: crop yields close to trees were one and a half times those of open field yields.

Another study from Burkina Faso (Tilander, 1996) recorded higher or similar yields in *A. indica* alleys compared to a treeless control, for the best treatments. The key factor was full coppicing of the trees early in the growing season. An alternative treatment, leaving part of the trees to grow stems, to ensure the practical interest of full-grown poles, was less advantageous. Mulching with the prunings seemed to have a weak additional effect in some cases. In the treatment combining full coppicing with mulching with the prunings, soil water content was higher in the alleys at a majority of occasions, compared with the control. Organic matter, total N, total P and pH were generally higher in the alleys (irrespective of treatment full/low-intensity coppicing; mulching/no mulching) after two years, compared with the control. It can be concluded that the conservation effects overruled any

Table 2. References to and experimental backgrounds in ten long-term (four or more years) semi-arid alley farming experiments

Study No.	Annual rainfall	Soil[1]	Years	Trees	Crops	Source
1	765	Shallow Alfisol	4 (1984-87)	leu	Pearl millet piegeonpea castor groundnut	Rao, M.R., Sharma, M.M. and Ong, C.K. 1991
2	830	Luvisols	6 (1986-91)	leu *Azadirachta indica* *Albizia lebbeck*	Sorghum	Tilander, Y., Ouédraogo, G. and Yougma, F. 1995
3	765	Vertic Inceptisols	4 (1984-87)	leu	Sorghum pigeonpea	Rao, M.R., Sharma, M.M. and Ong, C.K. 1990
4	750	Khandic Rhodustalfs	5 (1987-92)	leu *Cassia siamea*	Maize	Jama, B.A., Nair, P.K.R. and Rao, M.R. 1995
5	728	Alfisol/Lixisol	4 (1991-94)	leu	Sorghum cowpea	Osman, M., Emmingham, W.H. and Sharrow, S.H. 1998
6	755	Khandic Rhodustalfs	6 (1989-95)	leu	Maize	Mathuva, M.N., Rao, M.R., Smithson, P.C. and Coe, R. 1998
7	750	Alfisol	4 (1984-87)	leu	Cowpea castor sorghum	Singh, R.P., Ong, C.K. and Saharan, N. 1989a
8	850-875	Ferric Luvisol	4 (1984-88)	leu *Cassia siamea* *Cajanus cajan*	Maize	Chiyenda, S. and Materechera, S.A. 1989
9	499	Haplic Lixisols	4 (1989-92)	leu *Faidherbia albida*	Maize	Chamshama S.A.O., Mugasha, A.G., Klvstad, A., Haveraaen, O. and Maliondo, S.M.S. 1998
10	836	Ferralsols	5 (1984-89)	*Calliandra calothyrsus* *Cassia spectabilis* *Leucaena diversifolia*	Beans sorghum	Balasubramanian, V. and Sekayange, L. 1991

[1]Soil information is as given by authors, translation between different calassification systems has not been made.

competitive effects on soil water and nutrients in the alleys most appropriately managed.

A potential explanation for the advantage of early coppicing may be the increased nutrient supply to the crop following tree

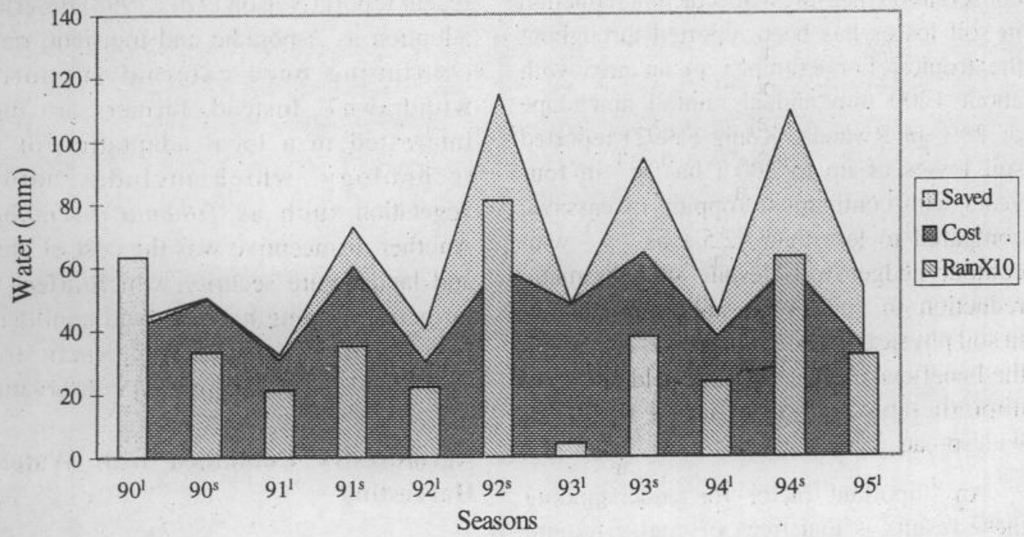

Fig. 2. Comparison of the water cost and water saved by Senna siamea contour hedgerows, Machakos, Kenya. l = long rains (March – July), s = short rains (October – February).

coppicing from dieback and decay of fine tree roots (van Noordwijk *et al.*, 1996). It has been suggested that use of different rooting zones for the tree and crop component is important for complementarity (Ong *et al.*, 1991; Odhiambo *et al.*, 1999). However, if the above mechanism can be further proved, it might on the contrary be an advantage if the trees and crops use the same rooting zone, provided that the agroforestry management practises results in early coppicing. The validity of this hypothesis should be tested further in semi-arid conditions.

In summary, crop performance in alley farming is highly variable. An enormous challenge exists in understanding the mechanisms behind as to how resource competition has been overcome in the fifteen (out of 28) cases where crop yields in semi-arid alley farming, were equal to or above sole crop yield (Table 3). This constitutes a major motive for further research. The question if a yield ratio of 1 or higher between treatment and control is good enough should be raised. In the short term, the cost of extra labor requirement needs to be balanced against benefits of the wood yield plus possible extra crop yield. Such decisions are best taken on the individual farm household level. In the long term the degree of soil conservation must be evaluated.

Contour hedgerows

Contour hedgerows with shrub legumes have consistently been promoted for soil conservation of sloping lands in the tropics because of their potential to sustain crop yields by controlling erosion and recycling nitrogen, and their relatively low input requirements relative to structural soil conservation measures. Spectacular reduction in soil losses has been reported throughout the tropics. For example, in an area with about 1200 mm annual rainfall and slope of 28% in Rwanda, Konig (1992) reported soil losses of up to 300 t ha^{-1} y^{-1} in four years with continuous cropping of cassava, compared to less than 12.5 t ha^{-1} y^{-1} with contour hedgerows. Despite such dramatic reduction in soil losses and improvement in soil physical properties (Agus *et al.*, 1997), the beneficial effects on crop yield are often unpredictable and insufficient to attract widespread adoption.

An important factor for understanding these results is that trees of course require water even when there is no runoff and that drought is more frequent than floods. For example, Ong *et al.* (1996b) made a comparison of the water saved or conserved by *Senna siamea* hedgerows on a 14% slope and the water transpired by the trees over eleven successive seasons at Machakos, Kenya, and found that the water cost exceeded the amount saved by 3 to 4 times (Fig. 2). In addition, crop yield was reduced by 30% and soil loss was reduced from 19 t ha^{-1} to 0.5 t ha^{-1}. In spite of this, contour hedgerow was more efficient as a soil and water conservation technique than napier grass strips, which was widely adopted in the area. In this region farmers prefer grass strips because it is considered as a more reliable fodder crop than maize. Therefore, trees for contour hedgerows should provide valuable products (pigeonpea) as well as conserving soil and water resources.

In the Philippines, sustained and considerable efforts have been committed to research and extension to facilitate the adoption of the contour hedgerows, yet a recent report (Nelson *et al.*, 1998) described adoption as "sporadic and transient, rarely continuing once external support is withdrawn". Instead, farmers are more interested in a local adaptation of the technology, which includes natural vegetation such as *Tithonia diversifolia*. Another disincentive was the cost of credit and land tenure security, which affect the farmers' planning horizons and confidence with which they expect to benefit from long term investments in soil conservation.

Agroforestry Combined with Water Harvesting

Some combinations of agroforestry systems and water-harvesting techniques look promising. In arid zones in Israel (115 mm rainfall, range 55 to 180 mm over 14 years) *Eucalyptus occidentalis* and *Acacia salicina* were planted in artificially constructed catchments of 0.35 ha (Zohar *et al.*, 1988). The recorded production of wood showed that a family of five would need 0.4 to 0.5 ha to meet its fuelwood demand in a two-year rotation. Residual water was present at 0 to 60 cm depth, which could possibly be utilized for crop production.

Water-harvesting rock barriers in Burkina Faso have been widely accepted by farmers and have had a major impact on entire regions (Wright and Bonkoungou, 1986). Farmers plant trees along the contour barriers where trees and bushes can also regenerate naturally. Rock barriers have been shown to increase yields by up to 100%, although it is uncertain for how long yields can be maintained at such high levels (Reij *et al.*, 1988).

Table 3. Best bet yield ratios and experimental backgrounds in eleven long-term (four or more years) semi-arid alley farming experiments

Study No.	Country	Location	Climate	Tree + crop	Yield ratio	Best bet	Comments to best bet
7b	India	Hyderabad	Semi-arid, bimodal	leu[1] + castor	0.1-0.4	0.4	
1c	India	Patancheru	Semi-arid, bimodal	leu + castor	0.22-0.50	0.5	n y = 1
1b	India	Patancheru	Semi-arid, bimodal	leu + pigeonpea	0.34-0.56	0.56	n y = 2
2a	Burkina Faso	Central plateau	Semi-arid, unimodal	leu + sorghum		0.56	
3a	India	Patancheru	Semi-arid, bimodal	leu + sorghum	0.15-0.62	0.62	Widest spacing (4.95 m), closest gap between hedge and crop (45 cm)
5a	India	Hyderabad	Semi-arid biomodal	leu + sorghum	0.37-0.83	0.83	
6	Kenya	Machakos	Semi-arid, bimodal	leu + maize	0.70-0.85	0.85	Prunings as mulch better than fed to oxen and returned as manure
4a	Kenya	Machakos	Semi-arid, bimodal	leu + maize	0.83-0.86	0.86	Density tree:crop 25:75 (compared to 15:85, 20:80)
1a	India	Patancheru	Semi-arid, bimodal	leu + pearl millet	0.50-0.88	0.88	n y = 2
3b	India	Patancheru	Semi-arid, bimodal	leu + pigeonpea	0.50-1.11	0.93	Second widest spacing (4.95 m), closest gap between hedge and crop (45 cm), n y = 3
7c	India	Hyderabad	Semi-arid, bimodal	leu + cowpea	0.3-1.0	0.95	10 m spacing, base data not presented in paper
7a	India	Hyderabad	Semi-arid, bimodal	leu + sorghum	0.4-0.8	1	5 m spacing, base data not presented in paper
8a	Malawi	Lilongwe	Semi-arid, unimodal	leu + maize	0.76-1.01	1.01	50 kg N ha^{-1} (compared to 0 and 100), 5.4 m alley width (compared to 2.7 m and 10.8 m)
9a	Tanzania	Morogoro	Semi-arid, unimodal	leu + maize	Nt[2]	1.05	Pruned early at planting, no inorganic, fertilizers
5b	India	Hyderabad	Semi-arid, bimodal	leu + cowpea	0.44-1.07	1.07	
1d	India	Patancheru	Semi-arid, bimodal	leu + groundnut	0.27-1.13	1.13	n y = 1, 3 m alleys, early pruning, polythene barriers at 0.5 m depth

Table 3 contd...

Table 3. contd...

Study No.	Country	Location	Climate	Tree + crop	Yield ratio	Best bet	Comments to best bet
10f	Rwanda	Karama	Semi-arid, bimodal	*Leucaena diversifolia* + sorghum	1.01-1.23	1.23	Manure (compared to no manure), calculated from figure
10e	Rwanda	Karama	Semi-arid, bimodal	*Leucaena diversifolia* + beans	1.31-1.42	1.42	No manure (compared to manure), calculated from figure
10d	Rwanda	Karama	Semi-arid, bimodal	*Calliandra colothyrsus* + sorghum	1.05-1.22	1.22	Manure (compared to no manure), calculated from figure
10c	Rwanda	Karama	Semi-arid, bimodal	*Calliandra colothyrsus* + sorghum	1.05-1.22	1.28	No manure (compared to manure), calculated from figures
8b	Malawi	Lilongwe	Semi-arid, unimodal	*Cassia siamea* + maize	0.60-1.01	1.01	10.8 m alley width (compared to 2.7 m and 5.4 m)
4b	Kenya	Machakos	Semi-arid biomodal	*Cassia siamea* + maize	1.03-1.10	1.10	Density tree:crop 25:75 (compared to 15:85, 20:80)
10a	Rwanda	Karama	Semi-arid, bimodal	*Cassia spectabilis* + beans	1.47-2.02	2.02	No manure (compared to manure), calculated from figure
10b	Rwanda	Karama	Semi-arid, bimodal	*Cassia spectabilis* + sorghum	1.42-1.58	1.58	No manure (compared to manure), calculated from figure
2c	Burkina Faso	Central plateau	Semi-arid, unimodal	*Albizia lebbeck* + sorghum	0.63-0.84	0.84	5 m spacing (compared to 8 m)
9b	Tanzania	Morogoro	Semi-arid, unimodal	*Faidherbia albida* + maize	Nt	0.99	Pruned early at planting, no inorganic fertilizers
2b	Burkina Faso	Central plateau	Semi-arid, unimodal	Neem + sorghum	0.82-1.0	1.00	8 m spacing (compared to 5 m)
8c	Malawi	Lilongwe	Semi-arid, unimodal	*Cajanus cajan* + maize	0.80-1.04	1.04	

[1] = *Leucaena leucocephala*, [2] = Not tested.

Dissussion

Is agroforestry in drylands sustainable? Or in other words, can conservation of growth resources by agroforestry or development of under-utilized niches be sufficient to overcome competition and maintain the natural resource base? As demonstrated above, this is often the case. Sustainable production in the short term (four or more years) is achievable even in some systems with high tree density (Table 3). However, this does not necessarily mean that the second part of the definition by Young (1989b)[1], regarding the conservation of the natural resources base, has been met. Extensively managed systems like the cultivated tree savannah or the traditional parkland systems are sustainable both as regards production and conservation with low population pressure. It is recognized that these systems are no longer sustainable due to the current and growing human population. Can the carrying capacity of such marginal and degraded lands be increased without additional input? Generally, when resource competition between species increases in intensively managed systems where high outputs are desired and plant density is elevated (as in the alley farming system), the risk increases for over-exploitation of available production resources (water and nutrients). It is, therefore, vital to examine new agroforestry systems regarding the conservation criteria of sustainability.

Available studies of both extensive (parklands) and intensive (alley farming) systems show potential for conservation in soil variables relevant for crop growth. However, it is well recognized that much of sub-Saharan Africa cannot support further agricultural intensification in terms of P (Breman and Kessler, 1995; Sanchez, 1994; Buresh and Tian, 1997). Furthermore, in many parts of the semi-arid tropics, the sources of organic matter cannot fully compensate for P deficiencies, even if biomass production is increased through agroforestry. Therefore, research is urgently needed in order to define optimal combinations of organic and inorganic fertilizers, especially P, for these soils (Sanchez, 1994). In view of the many resource-poor farmers in the region, it may be better to introduce income-generating trees in order to obtain cash to purchase fertilizers for food production (Leakey *et al*., 1999, this issue). In semi-arid Kenya, some farmers have developed new agroforestry systems, which are more akin to the scattered savannah ecosystems but still provide both household needs and cash for the family. Exciting agroforestry systems based on a local tree, *Melia volkensii* (a relative of the neem), is now receiving researchers' attention at ICRAF (Stewart and Bromley, 1994). Researchers are keen to determine why and how farmer's management of competition between melia trees and crops can be extended to other tree species and other dryland areas. Generally, trees are planted at 50 to 80 m spacing and heavily pruned from year two to provide good quality timber and prunings that are used for firewood and fodder. Melia trees shed their leaves during part of the wet season and seldom compete with crops. Farmers claim that the trees are deep rooting and enhance soil fertility from leaf and fruit litter.

Attention has to be drawn to the limited number of species tested in especially high density semi-arid agroforestry because tree

[1] Young (1989b) defines sustainable land use as:
"that which maintains an acceptable level of production and at the same time conserves the basic resources on which production depends, so enabling production to be maintained".

characteristics have a major influence on the outcome of conservation and competition effects. In parkland systems, many local species are used and diversity should be maintained (Leakey *et al*., 1999, this issue). However, it is doubtful if the traditional parkland systems offer sufficient possibilities for the necessary intensification, even if some advancement may be achieved by using improved dwarf fruit trees (Leakey *et al*., 1999, this issue). Therefore, dense systems with fast-growing species also have to be used. Young (1997) refers to 50 published alley farming studies and notes that two species are most frequently studied (*L. leucocephala and Gliricidia sepium*). Seven species are commonly studied and fourteen appear occasionally. In semi-arid studies the choice of species is even more limited. In the ten semi-arid studies examined in our paper (Table 3), it can be seen that nine species appear, with a massive attention on *Leucaena leucocephala* (in nine of the ten studies). The remaining species have only been tested in one or two cases. There is an urgent need to test more species, as well as re-examining species showing good results but only tested once or twice, to broaden the information base.

L. leucocephala has been shown to be too competitive as reported above and shows high tree mortality after repeated coppicing (noted also for *A. lebbeck*, Tilander *et al*., 1995). Ability to sustain repeated coppicing is an important long term effect that has to be considered for all species suggested for agroforestry involving coppicing. Surprisingly, neem is rarely studied, although it is very popular with farmers in the Sahel and in India. In a review it has been called "one of the most valuable multi-purpose species least exploited amongst tropical trees" (Tewari, 1992). It is famous for its pesticidal and pharmacological properties and research is focused on this (Koul *et al*., 1990; Schmutterer, 1984). However, in studies from semi-arid Burkina Faso, it has also been shown to be an excellent species for agroforestry. It coppices well in alley farming and parklands, and was found to produce higher amounts of leaf and wood biomass compared with other alley-farmed species (Tilander *et al*., 1995), with crop yields being equal or higher as compared to sole crops in both alley farming and parklands (Tilander, 1996). Neem leaf mulch was also shown to combine high nutrient delivery with water conservation, leading to higher yields and improved soil status compared to other mulches or the non-treated control (Tilander and Bonzi, 1997). In conclusion, neem should be recommended for further testing for intensive management in agroforestry systems in the semi-arid tropics.

In earlier work from a very dry environment (the Sahelian rangelands, 100 to 600 mm rainfall), it was concluded that primary production was limited by nutrient availability rather than water supply (Penning de Vries and Djitèye, 1982). The common belief that competition for water is always the dominant interaction in drylands is therefore contradicted. To understand this rather surprising fact, it should be noted that losses of water in this system, as mentioned (Breman and Uithol, 1984), may be very high. The potential for water conservation is, therefore, high and when water, as mentioned above, is conserved through agroforestry possibly combined with water conservation measures, nutrients are likely to become limiting and competition for nutrients between tree and crop may exist.

A maintained – or increased – soil organic matter content, as well as water conservation, are prerequisites for the optimal use of external inputs like inorganic fertilizers. Much recent debate has dealt with promoting high-input or low-input technologies, but such controversy is not helpful (Harrison, 1987; IIED, 1996). Low-cost technologies, like agroforestry and soil and water conservation measures, are indispensable basic components of sustainable agriculture production in the fragile drylands. If external inputs eventually become economically feasible, the low-input technology measures taken today will have provided – and will continue to provide – the necessary basis for an environmentally sound introduction of high-input technologies. For example, a good organic matter status and soil structure are indispensable for realizing the full potential of inorganic fertilizers.

This reasoning can probably be applied to all areas in the semi-arid tropics, where small farmers today do not have the funds necessary to make large investments, but are more than willing to consider low-cost improvements. Local differences in both social and physical conditions will, however, have to be considered. If the measures recommended are to succeed, the priorities (often food) and possibilities (often limited by labor and capital) must always be taken into account.

In summary, there is good potential for approaching sustainability in agroforestry systems in the semi-arid tropics in terms of both the production and conservation criteria. As for conservation, one move in this direction would be to increase the speed of the nutrient fluxes through pruning, which enhances the availability of nutrients available to the crops per unit time. Furthermore, the leaf-mulching material produced in connection with pruning can help to reduce losses of water, organic matter and nutrients.

Conclusions

The main impression from the available literature is that nutrients tend to be conserved in dryland agroforestry. Little has been reported about direct competition for nutrients between trees and crops. Attention must be given to the general decrease of soil nutrients during the last decades, especially in African soils. The suboptimal levels of P in many soils is particularly alarming in this respect and even if very tight nutrient cycles are maintained by agroforestry, there is simply not enough P in the soil.

With regard to water, competition has been reported to be a major interaction effect in many semi-arid agroforestry systems. However, there is also scope for reducing the competition by water-conservation /water harvesting linked to agroforestry.

Agroforestry is clearly an option in drylands. Natural ecosystems, such as the savannah, and traditionally managed systems, such as the cropped parkland, demonstrate that it is a sustainable system. However, competition tends to be more severe either when resources are scarce or when the systems are intensive with high tree density. This has been shown to be true for water competition in agroforestry, but competition for nutrients can not be excluded. Two main ways exist to avoid competition and to make use of the nutrient and water conservation potential in semi-arid agroforestry. These are: 1) to use an appropriate agroforestry design, and 2) to practice skilled management of the system. In this way, under-utilized niches may be developed.

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